

# High-energy direct reactions with exotic nuclei and low-energy nuclear astrophysics

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**Abstract.** Indirect methods in nuclear astrophysics are discussed. Recent work on Coulomb dissociation and an effective-range theory of low-lying electromagnetic strength of halo nuclei is presented. Coulomb dissociation of a halo nucleus bound by a zero-range potential is proposed as a homework problem (for further references see G. Baur and S. Typel, nucl-th/0504068). It is pointed out that the Trojan-Horse method (G. Baur, F. Rösel, D. Trautmann and R. Shyam, Phys. Rep. 111 (1984) 333) is a suitable tool to investigate subthreshold resonances.

## 1. INTRODUCTION AND OVERVIEW

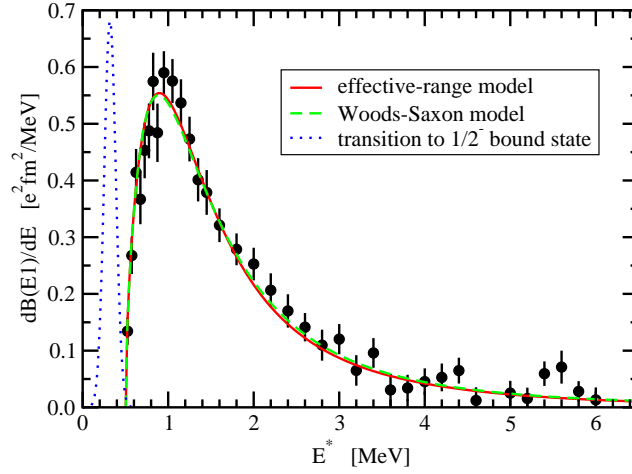
With the exotic beam facilities all over the world - and more are to come - direct reaction theories are experiencing a renaissance. We give a minireview of indirect methods for nuclear astrophysics reporting on recent work on Coulomb dissociation of halo nuclei [1, 2] and on transfer reactions to bound and scattering states. The chemical evolution of the universe and the role of radioactive beams has recently been reviewed in [3]. In [4] it is remarked that high energy (radioactive) beams are a valuable tool to obtain information on low energy nuclear reactions of astrophysical importance. We discuss Coulomb dissociation [5] and the Trojan Horse method [6, 7] as examples.

Coulomb dissociation of a neutron halo nucleus in the limit of a zero-range neutron-core interaction in the Coulomb field of a target nucleus can be studied in various limits of the parameter space and rather simple analytical solutions can be found. We propose to solve the scattering problem for this model Hamiltonian by means of the various advanced numerical methods that are available nowadays. In this way their range of applicability can be studied by comparison to the analytical benchmark solutions, for work in this direction see [8].

The Trojan-Horse Method [9, 10] is a particular case of transfer reactions to the continuum under quasi-free scattering conditions. Special attention is paid to the transition from reactions to bound and unbound states and the role of subthreshold resonances. Since the binding energies of nuclei close to the drip line tend to be small, this is expected to be an important general feature in exotic nuclei.

## 2. EFFECTIVE RANGE THEORY OF HALO NUCLEI

At low energies the effect of the nuclear potential is conveniently described by the effective-range expansion [11]. An effective-range approach for the electromagnetic strength distribution in neutron halo nuclei was introduced in [1] and applied to the single neutron halo nucleus  $^{11}\text{Be}$ . Recently, the same method was applied to the description of electromagnetic dipole strength in  $^{23}\text{O}$  [12]. A systematic study sheds light on the sensitivity of the electromagnetic strength distribution to the interaction in the continuum. We expose the dependence on the binding energy of the nucleon and on the angular momentum quantum numbers. Our approach extends the familiar textbook case of the deuteron, that can be considered as the prime example of a halo nucleus, to arbitrary nucleon+core systems, for related work see [13, 14, 15]. We also investigate in detail the square-well potential model. It has great merits: it can be solved analytically, it shows the main characteristic features and it leads to rather simple and transparent formulae. As far as we know, some of these formulae have not been published before. These explicit results can be compared to our general theory for low energies (effective-range approach) and also to more realistic Woods-Saxon models. Due to shape independence, the results of these various approaches will not differ for low energies. It will be interesting to



**FIGURE 1.** Reduced probability for dipole transitions as a function of the excitation energy  $E^* = E + S_n$  in comparison to experimental data extracted from Coulomb dissociation of  $^{11}\text{Be}$  [18].

delineate the range of validity of the simple models.

Our effective-range approach is closely related to effective field theories that are nowadays used for the description of the nucleon-nucleon system and halo nuclei [16]. The characteristic low-energy parameters are linked to QCD in systematic expansions. Similar methods are also used in the study of exotic atoms ( $\pi^-A$ ,  $\pi^+\pi^-$ ,  $\pi^-p$ , ...) in terms of effective-range parameters. The close relation of effective field theory to the effective-range approach for hadronic atoms was discussed in Ref. [17].

In Fig. 1 we show the application of the method to the electromagnetic dipole strength in  $^{11}\text{Be}$ . The reduced transition probability was deduced from high-energy  $^{11}\text{Be}$  Coulomb dissociation at GSI [18]. Using a cutoff radius of  $R = 2.78$  fm and an inverse bound-state decay length of  $q = 0.1486$  fm $^{-1}$  as input parameters we extract an ANC of  $C_0 = 0.724(8)$  fm $^{-1/2}$  from the fit to the experimental data. The ANC can be converted to a spectroscopic factor of  $C^2S = 0.704(15)$  that is consistent with results from other methods. In the lowest order of the effective-range expansion the phase shift  $\delta_l^j$  in the partial wave with orbital angular momentum  $l$  and total angular momentum  $j$  is written as  $\tan \delta_l^j = -(xc_l^j \gamma)^{2l+1}$ , where  $\gamma = qR = 0.4132 < 1$  is the halo expansion parameter and  $x = k/q = \sqrt{E/S_n}$  with the neutron separation energy  $S_n$ . The effective range term  $\frac{1}{2}r_l k^2$  term can be neglected, since it leads to a contribution with an extra  $\gamma^2$  factor which is small in the halo nucleus limit  $\gamma \rightarrow 0$  (at least in the case where the scattering length is of natural order). The parameter  $c_l^j$  corresponds to the scattering length  $a_l^j = (c_l^j R)^{2l+1}$ . We obtain  $c_1^{3/2} = -0.41(86, -20)$  and  $c_1^{1/2} = 2.77(13, -14)$ . The latter is unnaturally large because of the existence of a bound  $\frac{1}{2}^-$  state close to the neutron breakup threshold in  $^{11}\text{Be}$ .

The connection of the scattering length  $a_l$  and the bound state parameter  $q$  for  $l > 0$  is given by  $a_l = \frac{2(2l-1)R^{2l-1}}{q^2(2l+1)!!(2l-1)!!}$ . This is a generalization of the well-known relation  $a_0 = 1/q$  for  $l = 0$  in a square well model, where  $R$  denotes the range of the potential. The  $p_{1/2}$  channel in  $^{11}\text{Be}$  is an example for the influence of a halo state on the continuum. The binding energy of this state is given by 184 keV, which corresponds to  $q = 0.094$  fm. With  $R = 2.78$  fm one has  $\gamma^2 = 0.068$ . For  $l = 1$  one has  $a_1 = \frac{2R^3}{3\gamma^2} = 210$  fm $^3$  which translates into  $c_1 = (a_1/R^3)^{1/3} = 2.14$ . This compares favourably with the fit value given in table 1 of [1]: 2.77(13, -14).

For a further discussion we refer to [1].

### 3. A SOLVABLE MODEL FOR COULOMB DISSOCIATION OF NEUTRON HALO NUCLEI

We consider a three-body system consisting of a neutron  $n$ , a core  $c$  and an (infinitely heavy) target nucleus with charge  $Ze$ . The Hamiltonian is given by

$$H = T_r + T_{r_c} + V_{cZ}(r_c) + V_{nc}(r) \quad (1)$$

where  $T = T_r + T_{r_c}$  is the kinetic energy of the system. The Coulomb interaction between the core and the target is given by  $V_{cZ} = ZZ_c e^2 / r_c$  and  $V_{nc}$  is a zero-range interaction between  $c$  and  $n$ . The  $s$ -wave bound state of the  $a = (c + n)$  system is given by the wave function  $\Phi_0 = \sqrt{q/(2\pi)} \exp(-qr)/r$ , where  $q$  is related to the binding energy  $E_b$  by  $E_b = \hbar^2 q^2 / (2\mu)$  and the reduced mass of the  $c + n$  system is denoted by  $\mu$ . This system can be studied analytically in various approximations. It can serve as a benchmark for the comparison of various analytical as well as numerical approaches. We refer to [19] (see especially Ch. 4 there) for details.

The kinematics of the breakup process is given by  $\vec{q}_a \rightarrow \vec{q}_{cm} + \vec{q}_{rel}$  where  $\vec{q}_{cm}$  and  $\vec{q}_{rel}$  are directly related to  $\vec{q}_c$  and  $\vec{q}_n$ , respectively. Analytic results are known for the plane-wave limit, the Coulomb-wave Born approximation (CWBA, “Bremsstrahlung integral”) and the adiabatic approximation [20]). A first derivation of the “Bremsstrahlung formula” was given by Landau and Lifshitz [21], it was improved by Breit in [22]; an early review is given in [23]. It was first applied to heavy ions ( $^{11}\text{Be}$ ) in [24].

In the plane-wave limit the result does not depend on  $q_a$  itself but only on the “Coulomb push”  $\vec{q}_{coul} = \vec{q}_a - \vec{q}_{cm}$ . In the semiclassical high energy straight-line and electric dipole limit, first and second order analytical results are available, as well as for the sudden limit. E.g., in the straight-line dipole approximation a shape parameter  $x = k/q$  and a strength parameter  $y = m_n \eta / [(m_n + m_c) b q]$  determine the breakup probability (in the sudden limit). The impact parameter is denoted by  $b$  and the Coulomb parameter is  $\eta = ZZ_c e^2 / (\hbar v)$ . In [25] it was found that the breakup probability is given in leading order by

$$\frac{dP_{LO}}{dk} = \frac{16}{3\pi q} y^2 \frac{x^4}{(1+x^2)^4} \quad (2)$$

and in next-to-leading order by

$$\frac{dP_{NLO}}{dk} = \frac{16}{3\pi q} y^4 \frac{x^2(5 - 55x^2 + 28x^4)}{15(1+x^2)^6}. \quad (3)$$

Depending on the parameter  $x$ , the latter contribution leads to an enhancement or a reduction of the breakup probability as compared to the leading-order result. Another important scaling parameter, in addition to  $x$  and  $y$ , is  $\xi = \omega b / v$ , where  $\hbar\omega$  is the excitation energy of the  $(c + n)$  system. In the sudden approximation we have  $\xi = 0$  and there is an analytical solution [26].

The dependence of the post-acceleration effect on the beam energy was studied in post-form CWBA in [8]. Postacceleration is very important for low beam energies and tends to diminish with high energies, see especially Sect. 4.2 of [19]. This may pose a problem for the CDCC approach at low beam energies. The choice of the Jacobi coordinates to represent the CDCC basis is discussed in [27].

### 4. RECENT EXPERIMENTAL RESULTS AND ASTROPHYSICAL APPLICATIONS

The status of Coulomb dissociation has been reviewed until about 2003 in [19]. In addition to the general theoretical framework, this review also contains a discussion of the experimental results along with their astrophysical significance. The last years saw progress for various cases. This is a very brief summary of the experimental results.

The  $^7\text{Be}(p, \gamma)^8\text{B}$  reaction plays a key role in the determination of the solar neutrino flux.  $^8\text{B}$  Coulomb dissociation experiments have been carried out over decades at RIKEN, MSU and GSI, with increasing beam energies. A careful analysis of the GSI  $^8\text{B}$  experiment ‘GSI-2’ is now available [28], see also [29]. Particular emphasis was placed on the angular correlations of the breakup particles. These correlations demonstrate clearly that  $E1$  multipolarity dominates. The deduced astrophysical  $S_{17}$  factor shows good agreement with most recent direct  $^7\text{Be}(p, \gamma)^8\text{B}$  measurements. High beam energies help to reduce higher order effects. The equivalent photon spectrum weights the  $E2$  contribution more than the  $E1$  contribution. This effect diminishes with increasing beam energy. Thus the high beam energy of 254 A MeV used at GSI helps to reduce the importance of the  $E2$  contribution.

The origin of  $^6\text{Li}$  in the early universe is an interesting topic at present [30].  $^6\text{Li}$  is produced via the  $\alpha + d \rightarrow ^6\text{Li} + \gamma$  radiative capture reaction in big bang nucleosynthesis. The  $S$  factor of this radiative capture reaction can be determined

in a  ${}^6\text{Li}$  Coulomb breakup experiment. (The fragility of  ${}^6\text{Li}$  is due to the large cross section of the  ${}^6\text{Li}(p, \alpha){}^3\text{He}$  reaction, see Ch. 5.3 below). The results of the  ${}^6\text{Li} \rightarrow \alpha + d$  Coulomb dissociation experiment at  $E_{{}^6\text{Li}} = 150$  A MeV at the KaoS spectrometer at GSI have recently been presented [31]. Compared to the pilot experiment with  $E_{{}^6\text{Li}} = 26$  A MeV [32], lower  $\alpha - d$  relative energies down to 50 keV could be reached with rather small error bars. Again, the high beam energy is very useful.

Experimental results for the Coulomb breakup of psd-shell neutron rich nuclei from GSI were presented in [33]. There is valuable spectroscopic information on various isotopes. The observed electromagnetic  $E1$  strength above the one-neutron threshold of neutron-rich C, Be, B and O isotopes is explained by a non-resonant transition of a neutron into the continuum. The effective-range theory of halo nuclei given in Ch. 2 is well suited to describe these effects. The neutron capture cross section for the  ${}^{14}\text{C}(n, \gamma){}^{15}\text{C}$  reaction, which is of astrophysical relevance, is also deduced. The discrepancy between the Coulomb dissociation experiments at GSI [33, 34] and MSU as well as with the  $(n, \gamma)$ -capture results from Karlsruhe still persists.

Recently the  $E1$ -strength above neutron threshold in the neutron-rich  ${}^{130}\text{Sn}$  and  ${}^{132}\text{Sn}$  isotopes was investigated in a Coulomb dissociation experiment at GSI [35]. Low lying strength was found ('pygmy resonance'). The authors conclude that 'this  $E1$  strength arises from oscillations of the excess neutrons but it is under debate to what extent a collective mode is formed'.

The explosive hydrogen burning process synthesizes nuclei in hot, dense and hydrogen-rich stellar environments. Proton capture processes are important to understand this rp-process. Progress has been achieved in the Coulomb dissociation of p-rich nuclei which is an indirect way to study these capture processes. There are examples of Coulomb dissociation of proton rich nuclei which allow to deduce S factors for  $(p, \gamma)$  reactions. T.Gomi et al. [36, 37] performed a Coulomb dissociation experiment on  ${}^{23}\text{Al}$  in order to study the stellar  ${}^{22}\text{Mg}(p, \gamma){}^{23}\text{Al}$  reaction. They determine the radiative width  $\Gamma_\gamma$  of the first excited state in  ${}^{23}\text{Al}$  by measuring the  ${}^{23}\text{Al} \rightarrow {}^{22}\text{Mg} + p$  Coulomb dissociation. The Coulomb breakup of  ${}^{27}\text{P}$  was studied in [38] in order to determine the S factor for the  ${}^{26}\text{Si}(p, \gamma){}^{27}\text{P}$  reaction. The  $E2$   $\gamma$ -decay width of the first excited state in  ${}^{27}\text{P}$  was extracted. Assuming the same  $E2/M1$  mixing ratio as the one for the mirror nucleus  ${}^{27}\text{Mg}$  the astrophysically interesting  $\gamma$ -width can be estimated. Coulomb dissociation experiments with  ${}^{23}\text{Al}$  and  ${}^{27}\text{P}$  are also planned at GSI with higher beam energies in the near future.

For heavier nuclei with increasing charge the continuum contributions will diminish, due to the increase of the Coulomb barrier. The S factor will be dominated by resonance contributions that can be calculated in the Hauser-Feshbach approach, if the statistical assumptions are fulfilled.

## 5. TRANSFER REACTIONS

Exotic nuclei have low thresholds for particle emission. It is expected that in transfer reactions one will often meet a situation where the transferred particle is in a state close to the particle threshold. In "normal" nuclei, the neutron threshold is around an excitation energy of about 8 MeV, and the pure single particle picture is not directly applicable. Much is known from stripping reactions like  $(d, p)$  and thermal neutron scattering, see, e.g., [39]. The single-particle strength is fragmented over many more complicated compound states. The interesting quantity is the strength function. It is proportional to  $\Gamma/D$  where  $\Gamma$  is the width and  $D$  the level spacing. One has  $\Gamma/D \ll 1$ , as can be estimated from a square well model (see, e.g., [39]).

For neutron rich (halo) nuclei the neutron threshold is much lower, of the order of one MeV. In this case the single-particle properties are dominant and the ideas developed in the following can become relevant, see also [40]. The level density is also much lower. In normal nuclei the level density at particle threshold is generally so high that the single-particle structure is very much dissolved. This can be quite different in exotic nuclei which can show a very pronounced single-particle structure.

### 5.1. Trojan-Horse Method

A similarity between cross sections for two-body and closely related three-body reactions under certain kinematical conditions [41] led to the introduction of the Trojan-Horse method [6, 42, 43, 9]. In this indirect approach a two-body reaction

$$A + x \rightarrow C + c \quad (4)$$

that is relevant to nuclear astrophysics is replaced by a reaction

$$A + a \rightarrow C + c + b \quad (5)$$

with three particles in the final state. One assumes that the Trojan horse  $a$  is composed predominantly of clusters  $x$  and  $b$ , i.e.  $a = (x + b)$ . This reaction can be considered as a special case of a transfer reaction to the continuum. It is studied experimentally under quasi-free scattering conditions, i.e. when the momentum transfer to the spectator  $b$  is small. The method was primarily applied to the extraction of the low-energy cross section of reaction (4) that is relevant for astrophysics. However, the method can also be applied to the study of single-particle states in exotic nuclei around the particle threshold.

The basic assumptions of the Trojan Horse Method are discussed in detail in [9], see especially Section 2 there. In view of a recent preprint [44] we give here a very short outline of the reasoning (see also [10]). The method is based on the assumption that the transfer of particle  $x$  is a direct reaction process, for which the well known DWBA description [45] is appropriate. In contrast to [44] no such assumption is needed for the subprocess  $A + x \rightarrow c + C$ , which is of interest in this context. Although the post- and prior forms are equivalent, it is simpler to use the post form DWBA. The equivalence of post and prior sum rules for inclusive breakup reactions are elucidated in [46]('IAV'), see also [47], where details also to the more formal aspects and further references can be found. The basic approximation of [9] is the surface approximation, which allows one to relate the T-matrix of the process (5) to the (on-shell) S-matrix elements of the astrophysical reaction (4). The surface approximation was checked numerically in the inclusive breakup formalism of IAV in [48]. It proved to be very well fulfilled in this example. This exercise can be performed for every individual case in a similar manner.

## 5.2. Continuous Transition from Bound to Unbound State Stripping

Motivated by this we look again at the relation between transfer to bound and unbound states. Our notation is as follows: we have the reaction

$$A + a \rightarrow B + b \quad (6)$$

where  $a = (b + x)$  and  $B$  denotes the final  $B = (A + x)$  system. It can be a bound state  $B$  with binding energy  $E_{bind} = -E_{Ax} (> 0)$ , the open channel  $A + x$ , with  $E_{Ax} > 0$ , or another channel  $C + c$  of the system  $B = (A + x)$ . In particular, the reaction  $x + A \rightarrow C + c$  can have a positive  $Q$  value and the energy  $E_{Ax}$  can be negative as well as positive. As an example we quote the recently studied Trojan horse reaction  $d + {}^6\text{Li}$  [49] applied to the  ${}^6\text{Li}(p, \alpha){}^3\text{He}$  two-body reaction (the neutron being the spectator). In this case there are two charged particles in the initial state ( ${}^6\text{Li} + p$ ). Another example with a neutral particle  $x$  would be  ${}^{10}\text{Be} + d \rightarrow p + {}^{11}\text{Be} + \gamma$ . The general question which we want to answer here is how the two regions  $E_{Ax} > 0$  and  $E_{Ax} < 0$  are related to each other. E.g., in Fig. 7 of [49] the coincidence yield is plotted as a function of the  ${}^6\text{Li}-p$  relative energy. It is nonzero at zero relative energy. How does the theory [9] (and the experiment) continue to negative relative energies? With this method, subthreshold resonances can be investigated rather directly. We treat two cases separately, one where system  $B$  is always in the  $(A + x)$  channel, with a real potential  $V_{Ax}$  between  $A$  and  $x$ . In the other case, there are also other channels  $C + c$ , at positive and negative energies  $E_{Ax}$ .

The cross section is a quantity which only exists for  $E_{Ax} > 0$ . However, a quantity like the S factor (or related to it) can be continued to energies below the threshold. An instructive example is the modified shape function  $\tilde{S}$  in Ch. 6 of [2]. In analogy to the astrophysical S factor, where the Coulomb barrier is taken out, the angular momentum barrier is taken out in the quantity  $\tilde{S}$ . As can be seen from table 3 or 4 of [2] the quantity  $\tilde{S}$  is well defined for  $x^2 < 0$ , with the characteristic pole at  $x^2 = -1$ , corresponding to the binding energy of the  $(A + x) = B$ -system.

We refer to [50] for further discussion.

## 5.3. Some recent experiments using the Trojan Horse Method for nuclear astrophysics

It is mainly the Catania group led by Claudio Spitaleri that has shown in many examples how the Trojan-horse method can be developed into a useful tool for nuclear astrophysics. Many interesting results have been obtained which we summarize very briefly below. An especially interesting aspect is the following:

At sufficiently low energies, electronic screening affects the cross section of astrophysical reactions. For a recent experimental study see [51], a theoretical analysis is provided in [52]. These effects depend on the laboratory

environments and can also be different from the astrophysical conditions. Due to the high beam energy in the Trojan Horse Method, there is no screening of the Coulomb potential by the electron cloud and one determines the bare nucleus astrophysical S factor. The knowledge of this bare S factor - derived with the help of an indirect method - is useful in judging the screening effects in the 'direct' reaction under specific laboratory conditions. One can also determine the S factor at higher energies where screening is negligible. For the application of the Trojan-horse method it is mainly necessary that the theoretical description yields the correct energy dependence, and not necessarily the absolute value of the cross section. Eventually one has to determine - by means of model calculations - the astrophysical S factor under the astrophysical conditions, this is the quantity one is most interested in. For a list of experiments see Sect. 6 and Tab. 1 of [9] and also the introduction of [53].

The two stable isotopes of Li with  $A = 6, 7$ , are valuable probes for conditions in the early universe. While it is safe to say that the issue is far from settled at the present times, input from nuclear astrophysics is certainly important. The formation of  ${}^6\text{Li}$  in the early universe proceeds mainly by the  $\alpha + d$  radiative capture process mentioned in Sect. 4, the reactions which destroy  ${}^6\text{Li}$  have been studied using the Trojan-horse method.

The destruction of  ${}^6\text{Li}$  can proceed by the reaction  $d({}^6\text{Li}, \alpha)\alpha$ . This reaction was studied by the Trojan Horse reaction  ${}^6\text{Li}({}^6\text{Li}, \alpha\alpha){}^4\text{He}$ , where one of the  $\alpha$  particles has to be considered as a spectator ('Trojan Horse') [54, 55, 56]. The spectator condition, i.e. small momentum transfer in the three-body reaction, is ensured by the quasi-free kinematics.

Another reaction which depletes  ${}^6\text{Li}$  is  $p({}^6\text{Li}, \alpha){}^3\text{He}$ . It was studied in [49] by means of the Trojan Horse reaction  ${}^2\text{H}({}^6\text{Li}, \alpha){}^3\text{He}n$ . Coincidence spectra were measured in a kinematically complete experiment at  $E_{{}^6\text{Li}} = 25$  MeV. They show the presence of the quasifree  ${}^6\text{Li}-p$  process. Cross sections for the  ${}^6\text{Li}(p, \alpha){}^3\text{He}$  from  $E_{cm} = 2.4$  MeV down to astrophysical energies were extracted. (Actually, the experimental results extend also to negative  ${}^6\text{Li}-p$ -energies).

The  ${}^{11}\text{B}(p, \alpha_0){}^8\text{Be}$  reaction was studied from 1 MeV down to astrophysical energies by means of the Trojan-horse method applied to the three-body reaction  $d({}^{11}\text{B}, \alpha_0){}^8\text{Be}n$  [53]. This reaction is responsible for the boron destruction in stellar environments.

The reaction  ${}^3\text{He}(d, p){}^4\text{He}$  was studied in [57] by means of the  ${}^6\text{Li}({}^3\text{He}, p\alpha){}^4\text{He}$  three-body reaction. The bare astrophysical  $S(E)$  factor was deduced. This allowed an independent estimate of the screening potential, confirming the discrepancy with the adiabatic limit. The reaction  ${}^3\text{He}(d, p){}^4\text{He}$  is important for primordial nucleosynthesis [52].

One may also envisage applications of the Trojan-horse method with exotic beams. An unstable (exotic) projectile hits a Trojan-horse target allowing to study specific reactions on exotic nuclei that are inaccessible in direct experiments. We mention the  $d({}^{56}\text{Ni}, p){}^{57}\text{Ni}$  reaction studied in inverse kinematics in 1998 [58]. In this paper, stripping to bound states was studied. In the meantime, more (d,p) transfer reactions were studied in inverse kinematics [59, 60, 61]. An extension to stripping into the continuum would be of interest for this and other kinds of reactions.

## 6. CONCLUSION

While the foundations of direct reaction theory have been laid several decades ago, the new possibilities which have opened up with the rare isotope beams are an invitation to revisit this field. The general frame is set by nonrelativistic many-body quantum scattering theory, however, the increasing level of precision demands a good understanding of relativistic effects notably in intermediate-energy Coulomb excitation.

The properties of halo nuclei depend very sensitively on the binding energy and despite the ever increasing precision of microscopic approaches using realistic NN forces it will not be possible, say, to predict the binding energies of nuclei to a level of about 100 keV. Thus halo nuclei ask for new approaches in terms of some effective low-energy constants. Such a treatment was provided in Ch. 2 and an example with the one-neutron halo nucleus  ${}^{11}\text{Be}$  was given. With the radioactive beam facilities at RIKEN, GSI and RIA one will be able to study also neutron halo nuclei for intermediate masses in the years to come. This is expected to be relevant also for the astrophysical r-process. It is a great challenge to extend the present approach for one-nucleon halo nuclei to more complicated cases, like two-neutron halo nuclei.

The treatment of the continuum is a general problem, which becomes more and more urgent when the dripline is approached. In the present proceedings we studied the transition from bound to unbound states as a typical example.

Recent experiments in the field of Coulomb dissociation and the Trojan-horse method are discussed. It is a rich and fruitful development.

Beautiful experiments have to be matched with good theoretical developments and painstaking analysis. While the Coulomb dissociation method relies essentially only on QED, precise experiments can give, in combination with a thorough theoretical analysis, precise answers for the astrophysical S factors. In the Trojan-Horse Method more

phenomenological aspects enter, like optical model parameters and effective nuclear interactions. This makes the interpretation of the experimental results in terms of astrophysical S factors less precise. However, this is not a new aspect in nuclear physics. In the interpretation of screening effects one relies on the accuracy of the energy dependence. This is certainly better fulfilled than the accuracy of the absolute values.

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